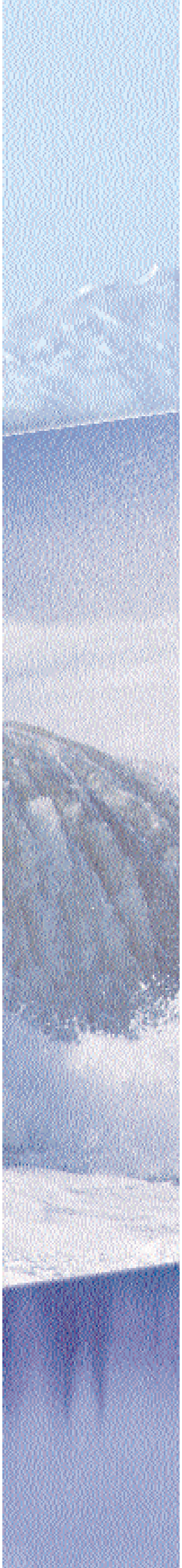

Reducing uncertainty about carbon dioxide as a climate driver

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The lack of an adequate ancient analogue for future climates means that we ultimately must use and trust climate models, evaluated against modern observation and our best geologic records of warm and cold climates of the past. Armed with an elevated confidence in the models, we will then be able to make reliable predictions of the Earth's response to our risky experiment with the climate system.

The world's industrialized nations have initiated a global experiment in climate change, unwittingly at first, knowingly now, but with great uncertainty and debate about its consequences. The experiment began to have detectable consequences (in retrospect) for atmospheric composition with the clearing of Northern Hemisphere forests in the nineteenth century. The signal intensified through the twentieth century with the continued destruction of forest globally and the exponential increase in the rate of combustion of fossil fuels, the release of methane and nitrous oxide from agricultural lands and livestock, and the production and subsequent loss to the atmosphere of synthetic freons (halogenated hydrocarbons). These gases are all of consequence for climate because they are greenhouse gases: they absorb infrared energy (heat) emitted from the Earth's surface and re-emit a substantial fraction of this energy back to Earth. Their direct effects on global energy balance can be readily calculated, but the climate system they are disturbing is complex, with numerous feedback mechanisms (interdependent cause–effect relationships) that create indirect effects that are more difficult to predict.

Although it is unlikely that these feedbacks could ever reverse the climatic response from warming to cooling, the transition to new states may involve counterintuitive transients. For example, the initial warming during the last deglaciation 12,000 years ago caused a temporary return to the glacial state (the Younger Dryas; see review in this issue by Rahmstorf, pages 207–214). Policy-makers (especially in the United States) have used such uncertainties to justify delaying action to mitigate against global warming. Fortunately, several scientific approaches are being taken to reduce the uncertainties, including process studies, numerical modelling, comparison of models with the recent climate record (see the review in this issue by Allen and Ingram, pages 224–232), and investigation of ancient climates. However, recent palaeoclimate studies[1–3] have stirred up scientific debate about the role of carbon dioxide as a climate driver and the importance of other feedback mechanisms, especially those involving water vapour, in climate change.

The role of water in the greenhouse effect

An important suite of climate processes involves atmospheric water — the amount of water vapour (itself a greenhouse gas) in the atmosphere, cloud cover and albedo (reflectivity) of the clouds, the transport of latent heat (water vapour) through the atmosphere and the intensity and distribution of rainfall. In fact, water vapour is the most important greenhouse gas, accounting for around two-thirds of the 33 °C of additional warming our planet receives because of the presence of its atmosphere. Given this, why are we concerned about the build-up of CO_2 and other greenhouse gases whose direct contributions to global warming are relatively small?

To understand the answer to this question we must distinguish 'external' versus 'internal' influences on the climate system. External influences include variations in insolation on a wide range of timescales, inputs of greenhouse gases and reflective aerosols from anthropogenic activities and natural processes such as volcanism, and, on geologic (million-year) timescales, the uplift of mountain belts and the geographical distribution of the continents. These factors are external to the climate system in the sense that although they affect climate, climate has no apparent reciprocal effect on them. (However, it has been suggested that climate may indeed influence mountain uplift and thus that tectonics is not strictly 'external' to the climate system[4]; additionally, policy changes in response to climate change may ultimately affect human activities such as fossil-fuel burning.)

External influences either perturb the climate system with short-duration disturbances (for example, injection of volcanic aerosols into the atmosphere, causing cooling; see review in this issue by Kaufman and co-workers, pages 215–223) followed by climatic response (often relaxation to the original state), or drive it with persistent forcing to new states. In this respect, not all external forcings are equal. For example, the cooling effect of sulphuric-acid aerosols produced by fossil-fuel combustion offsets some of the present warming resulting from fossil-fuel CO_2 emissions, but once the burning stops, the aerosol cooling will disappear within years to decades whereas the warming from CO_2 will last for millennia (and thus will affect other climatic factors such as the size of polar ice sheets).

In contrast, 'internal' climate influences are integral parts of the climate system, inseparably coupled through feedback mechanisms. Internal feedbacks include those that relate surface temperature to the water-vapour content and cloudiness of the atmosphere, to sea-ice coverage of the oceans, to the exchange of CO_2 between the oceans and atmosphere, and to the release of methane from wetlands. Internal feedbacks amplify or damp external forcings, but

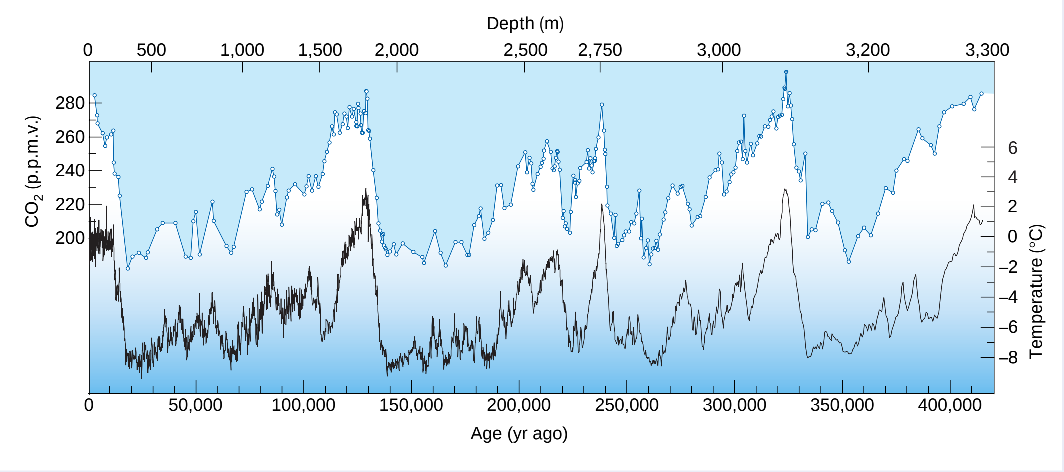

Figure 1 The variations in atmospheric carbon dioxide concentrations and relative changes in air temperature determined from the Vostok, Antarctica ice core are tightly correlated and reveal no obvious, substantial lead–lag relationship. Figure adapted from ref. 14, with permission.

cannot in themselves drive climate change. The increase in water-vapour content of the atmosphere in response to the initial warming from elevated atmospheric CO_2 partial pressure (pCO_2) is a positive feedback that amplifies the warming. An increase in cloudiness (in particular of low clouds; see Box 1 in the review by Pierrehumbert, pages 191–198) is a negative feedback that tends to damp the warming.

It is difficult to predict the extent of amplification or damping of the external forcings by internal feedbacks. Complex general circulation models of the climate system incorporate the current understanding of the nature of these feedbacks, and predict net warming well in excess of the direct effects of CO_2 for this century (see http://www.ipcc.ch for a current assessment of climate-change potential by the Intergovernmental Panel on Climate Change). Much of the extra warming is predicted to come from an enhanced greenhouse effect attributable to water vapour.

Reducing uncertainties in model predictions

There is considerable uncertainty in model predictions of climate change (see the review in this issue by Allen and Ingram, pages 224–232). This results in part from the coarseness of the gridded representation of spatially continuous physical processes that numerical models must adopt, especially as it affects our ability to predict cloud cover and rainfall. The climate system has processes acting at microscopic to megascopic scales, and the fine-scale processes (for example, the formation of clouds) must be parameterized rather than treated explicitly in global models.

There is also the possibility that the models are missing key climate feedbacks, with biotic processes perhaps being neglected most in previous models. State-of-the-art climate models have added interactions with terrestrial (land-based) ecosystems. For example, current models incorporate the ability of plants to pump vast amounts of water into the atmosphere through evapotranspiration and modify the surface albedo, thus affecting local energy budgets and precipitation. Fully interactive models also allow the vegetation type to change as the climate predicted by the model changes. However, most models neglect the potentially critical role that marine algae play in the formation and reflectivity of clouds over the remote ocean[5].

One approach to reducing model uncertainties is to evaluate how the climate system has responded to similar forcings in the geologic past. In doing so, palaeoclimatologists have discovered a number of climate paradoxes that challenge us to think in new ways about the climate system. The 400,000-year Vostok ice-core record of atmospheric pCO_2 and temperature would seem to provide the ideal demonstration that CO_2 drives climate (Fig. 1). The two records are highly positively correlated, with warm intervals occurring during times of elevated atmospheric pCO_2 and vice versa. But cause and effect is difficult to assign. On these geologically short timescales, changes in atmospheric pCO_2 are internal to the climate system, driven by exchanges of carbon among the ocean, atmosphere and terrestrial biomass that affect and are affected by climate change. In feedback loops, the comfortable concept of cause and effect loses its meaning, and so attempts to assign them usually end in frustration. The pacemaker of Pleistocene climate change seems to be subtle changes in the Earth's orbit around the Sun (see the reviews in this issue by Rahmstorf , pages 207–214, and Lambeck *et al.*, pages 199–206), but the climatic response clearly involves CO_2.

Climate models of the Last Glacial Maximum provide good support of the CO_2–climate connection. When the Earth's orbital parameters are set to favour glaciation, and the maximum extent of ice sheets in the Northern Hemisphere is specified but atmospheric pCO_2 is maintained at pre-industrial levels, these models fail to achieve cooling south of the Equator. However, when reduced atmospheric pCO_2 is added to the model specifications, the tropics and Southern Hemisphere cool[6], more in keeping with the data (in fact, such studies indicate that climate models may be underestimating the climatic sensitivity to changes in atmospheric pCO_2). Thus, despite all the uncertainties, climate models do reproduce the general features of the cooler climate of the last glacial interval, but only with reduced atmospheric pCO_2.

We need to look beyond the glacial record, though, if we want to be able to predict the future. The range of natural variability in atmospheric pCO_2 over the past 400,000 years, from approximately 180 to 280 parts per million by volume (p.p.m.v.), does not even include the present-day human-perturbed value of 370 p.p.m.v. We thus have no analogue in the Pleistocene glacial record for climates of the future, with atmospheric pCO_2 potentially reaching 2,000 p.p.m.v. upon complete utilization of the world's coal supplies. (The known coal reserves dwarf those of oil and natural gas in terms of their ability, upon utilization, to alter the CO_2 content of the atmosphere.)

Comparison with the geologic past

Compared with much of Earth's history, we live in a time of globally cool temperatures and (probably) low atmospheric pCO_2. A promising approach to the evaluation of climate response to greenhouse gas build-up, then, is the analysis of high-resolution palaeoclimate data sets from the more distant geologic past when warm climates prevailed. Based on these records, there are good reasons to suspect that atmospheric pCO_2 has been a primary climate driver[7], but the evidence is not conclusive. Certain intervals of the Earth's history, such as the Middle Cretaceous (about 100 million years (Myr) ago) are characterized by fossil and geologic indicators of global warmth, and by voluminous deposits of volcanic rocks and other indicators of abundant volcanism. Volcanoes are a chief source of CO_2 to the atmosphere, so it is reasonable to conclude that atmospheric pCO_2 was elevated during such times. However, the times of greatest volcanic activity may not correlate directly with times of greatest warmth[3]. Moreover, unlike the Pleistocene, there is no direct evidence for CO_2 levels in earlier times. Numerical carbon-cycle models that calculate ancient CO_2 levels, and pCO_2 proxies derived from the isotopic composition of marine organic matter or carbonate nodules in ancient soils, or from the density of stomata on fossil leaves, do generally support the relationship between climate and atmospheric pCO_2 on geologic timescales[7].

There is also proxy evidence that greenhouse gases (CO_2 and methane) have driven more rapid climate shifts. A recent analysis of stomatal density from plant fossils deposited just after the Cretaceous/Tertiary mass extinction (65 Myr ago) suggests that atmospheric pCO_2 may have risen to 1,000s of p.p.m.v., consistent with indicators of global warmth, and implicating meteorite impact into a limestone target area[8]. Cores of marine sediments also reveal highly detailed glimpses of climate history. For example, sediments providing 1,000-year temporal resolution offer compelling evidence that an abrupt warming at the Palaeocene/Eocene boundary (55 Myr ago) was caused by a massive release of methane from sea-floor gas-hydrate deposits[9]. The timescale and magnitude of the release are similar to the projected fossil-fuel pulse, so the event could potentially be an analogue for future climate change. However, the 1,000-year resolution is limiting in this respect, and future responses are likely to differ from those of a Palaeocene lacking continental ice sheets.

Mismatches in the CO_2–climate relation

Despite these successes in linking variations in greenhouse gas concentrations to climate change in the geologic past, the oxygen isotope palaeotemperature record from 600 Myr ago to the present displays notable intervals for which inferred temperatures and pCO_2 levels are not correlated[1]. One of these occurred during the early to middle Miocene (about 17 Myr ago), a time well established as a warm interval (relative to today), but with proxy evidence for low atmospheric pCO_2 (ref. 2). Moreover, whereas climate models predict tropical warming in response to elevated pCO_2, geologic data — in particularly the oxygen isotope record — indicate muted warming or even cooling at low latitudes while higher latitudes warm (the 'cool tropics paradox'[10–11]). A better understanding of what controls the latitudinal temperature gradient is clearly needed (see review in this issue by Pierrehumbert, pages 191–198). It is possible, however, that this paradox and the longer-term mismatch between pCO_2 and temperature proxies are artefacts, the consequence of inevitable blurring of the signal by geochemical processes that act on sediments after deposition on the sea floor[3,12].

Is the CO_2–climate relationship refuted by these apparent mismatches? I think not. Even if the proxies survive further scrutiny and the mismatches remain, we should not expect highly correlated records of volcanism and other external forcings, atmospheric pCO_2 and climate. In intricately coupled systems such as the climate system, with components acting on a wide range of timescales, responses of system state to stimuli can lag forcing significantly. CO_2 build-ups can lag elevated CO_2 inputs by millennia to millions of years because other processes damp the forcing; in such a case, we would expect the evidence for elevated inputs (for example, volcanic activity) to correlate instead with the rate of increase in atmospheric pCO_2. Similarly, a CO_2 increase whose radiative forcing drives a slow-changing climate component (for example, the extent of continental ice sheets during glaciation) could produce a proxy climate record (for example, ice-sheet volume as expressed in the oxygen isotopic composition of the ocean; see review in this issue by Lambeck *et al.* pages 199–206) that was poorly correlated with the CO_2 forcing.

This explanation for the out-of-phase relationship between climate and atmospheric pCO_2 may apply to the Miocene mismatch, but is best illustrated in the 'snowball Earth' scenario proposed for the Late Precambrian (750–600 Myr ago; see review in this issue by Pierrehumbert). The frozen Earth accumulates CO_2 from volcanoes for millions of years until the level is sufficiently high (perhaps hundreds of times the present level) to create a greenhouse effect that can overcome the cooling effect of highly reflective continental ice sheets and global sea-ice cover. Theoretically, CO_2 is highest at the end of the snowball interval, and then drops during the warmth of the ensuing deglaciation. A similar scenario was proposed for the more modest Late Ordovician glaciation (440 Myr ago)[13]. Moreover, if thresholds must be overcome before the system can change state, then relationships become highly nonlinear and may exhibit long periods of no correlation. Switches in ocean circulation patterns and their attendant effects on climate are good examples of threshold effects (see review in this issue by Rahmstorf, pages 207–214).

Perspectives

We have made the natural world our laboratory, but the experiment is inadvertent and thus not designed to yield easily decipherable results. Consequently, we will have difficulty isolating the effects of our manipulations from natural variations in climate until the signal has risen well above the noise (and the climate perhaps has been detrimentally altered). In looking into the past history of the planet for clues to the future, we find general support for the notion that an increase in atmospheric pCO_2 will cause global warming. However, in detail the relationship is neither linear nor in phase on all timescales. Proxy indicators of global warmth do not always coincide with proxy indications of elevated pCO_2, and when they do, as in the Late Pleistocene, there is no lead–lag relationship from which one might hope to assign cause and effect. Fortunately, improved models evaluated against expanded high-fidelity palaeoclimate databases are on the horizon, and should be adequate to support policy decisions concerning the reduction of fossil-fuel CO_2 emissions. In the meantime, there are unsettling indications that these models are underestimating rather than overestimating the climatic consequences of greenhouse gas build-up. □

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